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# Synchronous Reluctance Motors with Toroidal Windings

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**Abstract** -- This paper introduces the concept of a four-pole toroidally wound synchronous reluctance machine as an alternative to conventional and fractional slot concentrated winding designs. The toroidal windings, which are wound around the stator coreback have very short end windings, limiting the copper loss as with fractional slot concentrated windings, facilitating an increase in machine efficiency. However, unlike fractional slot concentrated windings, even space-harmonics in the air gap do not exist and the associated parasitic effects are minimized. The machine concept is described and its relationship with conventional and fractional slot concentrated winding machines is discussed. Construction methods are discussed with emphasis on manufacturability and the advantages and disadvantages of this topology are presented.

**Index Terms**-- AC motor drives, concentrated winding, rotating machines, toroidal windings, toroidally wound machines, reluctance motor, synchronous machine.

## I. INTRODUCTION

The synchronous reluctance machine (SynRM) has a resurgence in interest in both the industrial area [1] and the automotive market. Although these two research and investment streams are for different reasons, the machine topologies are generally the same. The former is linked to ever higher efficiency machine rating standards [2] to reduce greenhouse gas emissions and improve the generation, transmission and distribution network efficiency. The latter, is linked with the unstable price of NdFeB magnet material and the associated political and environmental issues [3]. All industrial synchronous reluctance machines utilize polyphase distributed windings [4-7], which are characterized by their long end windings (Fig. 1), which typically span a whole rotor pole pitch. This long end winding leads to a large amount of redundant copper (expense and mass) as well as excessive copper loss in the machine end region which is difficult to cool. These windings also typically have a low slot fill factor of around 0.35. The SynRM topology has not changed much since the original paper by Kostko in 1924 [8]. The major change is the introduction of the axially laminated variant of the SynRM [9] which has since faded into the past due to higher eddy current losses than traditionally laminated machines, despite its potential for superior performance. In an attempt to discover novel and viable topologies, a logical step

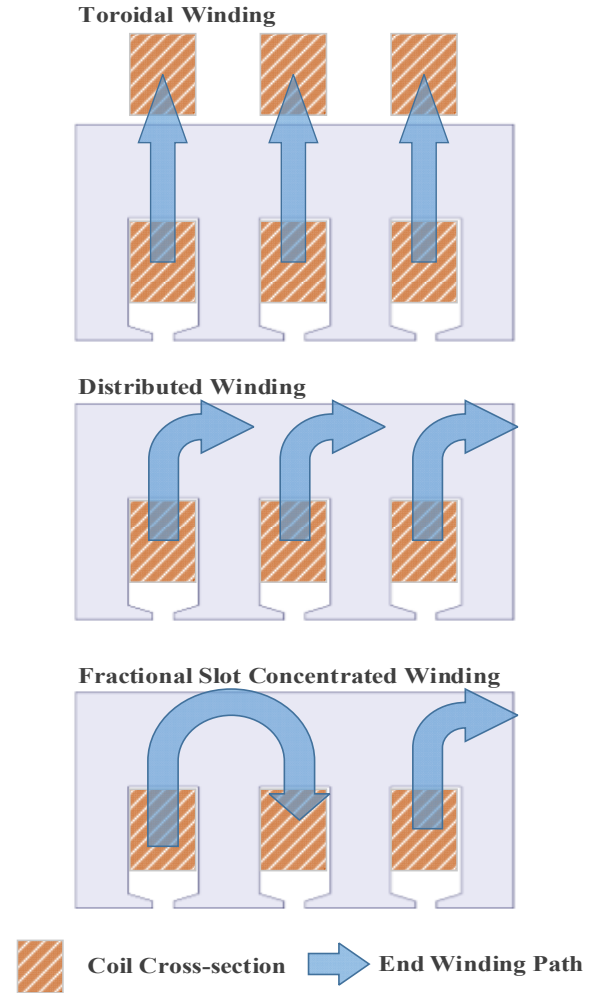


Fig. 1. Winding types for synchronous reluctance machines. Toroidal winding (top), conventional polyphase distributed winding (middle) and a fractional slot concentrated winding (bottom).

in advancing synchronous reluctance technology was to introduce fractional slot windings (FSCW), Fig. 1. The authors' have presented the FSCW topology as an alternative [3] and with higher pole numbers in [10]. This is due to their short end-windings and relative ease of construction, leading to lower cost and robust machines with higher efficiency [3]. Another type of winding that is non-overlapping with short end

windings is the toroidal winding [11] (Fig. 1), in which a coil is wrapped toroidally around the coreback of the machine. This type of winding was first presented in 1968 in a patent [12] for induction machines and subsequent work has shown its effectiveness [13] at Newcastle University, UK. They have also been investigated for double rotor permanent magnet machines [14] and switched reluctance [15] as well as a variant often employed in axial flux machines [16], however, no application of this winding to synchronous reluctance motors is found in the literature. This aim of this paper is to present the concept of the toroidally wound synchronous reluctance motor and assess its merits and drawbacks of application to such machines in comparison to conventional and fractional slot concentrated winding variants. Experimental testing of prototype machines is beyond the scope of this paper and will be presented in subsequent publications.

## II. TOROIDAL MACHINE CONCEPT

The concept of the toroidally wound synchronous reluctance motor (tSynRM) is as follows; a conventionally

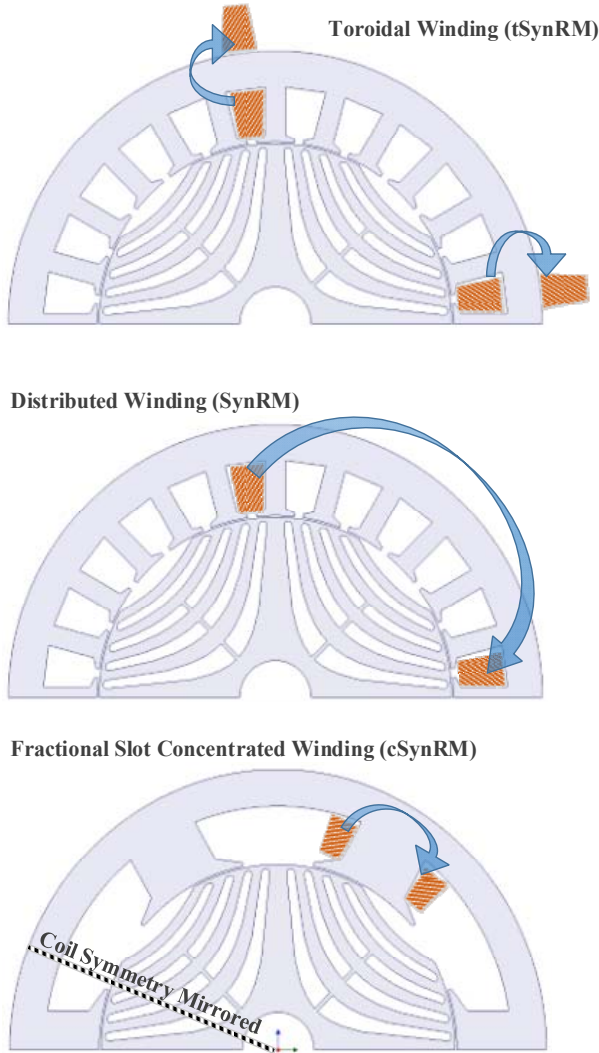


Fig. 2. Coil configurations for the various winding types.

designed synchronous reluctance motor can be rewound with a toroidal winding, rather than the concentric distributed winding usually found in small and medium frame size motors. This toroidal winding is wound around the coreback of the machine, opposed to being wound inside the slots as in the distributed and fractional slot concentrated winding machines (Fig. 2). From the geometry, there are a number of observations –

- End winding length is linked to the coreback depth and hence the rotor pole number
- The outer diameter of the machine is increased to accommodate the conductors and a special case will be required
- The toroidal coil does not link the full rotor pole flux
- Conductors appear as distributed windings at the stator bore – maintaining winding factor and low space harmonic MMF content

It is immediately obvious, that short end windings exist when compared to the distributed winding, similar to the fractional slot concentrated winding leading to lower coil length and copper loss. Synchronous reluctance machines usually consist of four rotor poles and therefore is what is considered in this paper. The outer diameter of the machine is required to be increased due to the return path conductors, which is a disadvantage and a special stator core insertion technique/arrangement will be required as to not damage the conductors. As the full airgap flux per pole is not linked by the coils, coils of consecutive poles are required to be connected in series, doubling the effective turns per phase, but the overall conductor length can remain the lower than a conventional machine due to significant end winding length reduction under certain circumstances. Only odd harmonics exist in the MMF and airgap waveforms due to the quasi-distributed nature of the conductors/coils, even harmonics are eliminated.

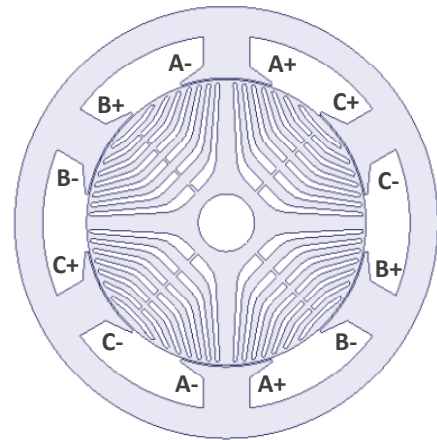


Fig. 3. Previously presented topology with non-overlapping fractional slot concentrated windings.

### III. THE cSynRM (FSCW)

Fractional slot concentrated windings and the cSynRM have been presented previously by the authors [3,10, 18] as an alternative topology to convention (Fig. 3). The cSynRM was of the three phase four pole, six tooth type, therefore the number of slots, per pole per phase was 0.5.

This machine typically has 30-40% lower copper length, leading to a machine efficiency increase. The machine is robust, low cost and easy to manufacture and exhibits superior thermal and torque density performance due to the achievable fill factor, typically above 55%, opposed to the conventional fill factor of between 30-35%. Thermal improvements are gained by reducing the amount of air in the slot.

Despite the benefits of the cSynRM, the machine topology suffers from undesirable characteristics derived from the nature of the windings. As the machines are fractional slot concentrated – they are short pitched and naturally exhibit even harmonics (Fig. 4) due to the asymmetrical MMF waveforms caused by discrete placement of the coils around the airgap periphery.

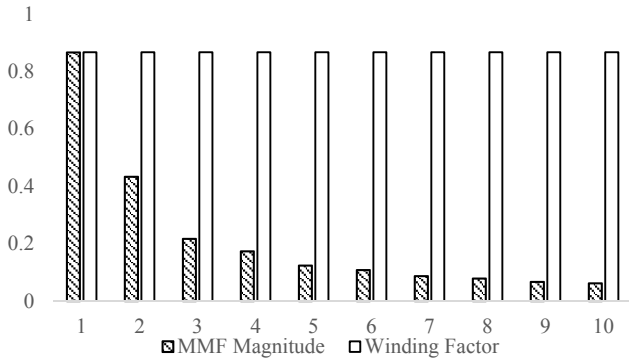


Fig. 4. The winding factors (unshaded) and MMF per-unit magnitudes (shaded) of the 6-slot 4-pole fractional slot concentrated winding.

In [3] the parasitic effects associated with the even harmonics are found;

- Increased leakage inductance (increased airgap leakage factor)
- Increased iron loss (harmonic fluxes)
- High torque ripple (perturbations in the Maxwell Stress tensor)
- Lower power factor

Compounding these parasitic effects, the lack of available slot-pole combinations is severely limiting in machine design and selection. The available slot pole combinations have a poor fundamental winding factor (typically  $<0.9$ ) compared to their distributed winding counterparts. The low tooth number required for low pole numbers also leads to a large Carters factor due to the wide slot openings. The cSynRM in [3] utilized double layer windings to minimize the space harmonic content and had a fundamental winding factor of 0.866.

Therefore, with the machines advantages come certain disadvantages. The concept of the toroidally wound machine (tSynRM) may go part way to solving some of these challenges without compromising much on the benefits;

- No even harmonics exist
  - Reduced torque ripple
  - Lower iron loss
  - Lower leakage inductance
- Maintain short end windings, non-overlapping coils, easy manufacture and robustness
- Numerous slot-pole combinations
- Higher fundamental winding factor

A conventionally or toroidal winding machine will have lower space harmonic content and higher winding factors. In Figure. 5 the space harmonics of a 36 slot tSynRM are compared with a 6 slot cSynRM.

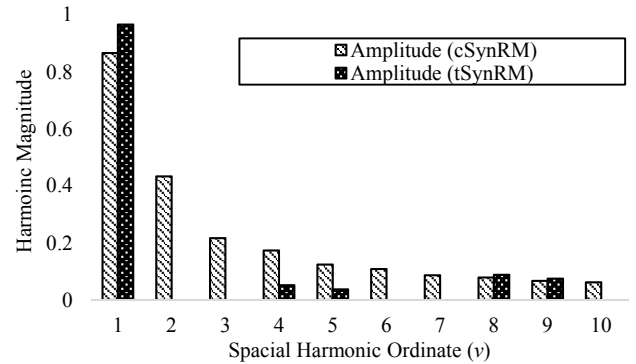


Fig. 5. MMF harmonics of a 36 slot, 4 pole tSynRM and MMF harmonics of a 6 slot, 4 pole cSynRM

The disadvantage of the toroidal winding topology is that the return path conductors do not participate in any torque production. A well designed tSynRM must ensure that the overall winding length is shorter than a conventionally wound machine in order for there to be any benefit, this will be discussed in a later section, where the remainder of this paper is dedicated to the application, construction and expected machine performance and characteristics of the tSynRM machine topology. Methods of construction as well as the expected machine performance and design issues are discussed.

### IV. MACHINE CONSTRUCTION AND COIL WINDING

In order to maintain the good slot fill factor, the coils should be wound without the stator component assembled. This is similar to author's cSynRM [3] where interlocking stator segments are used to bobbin wind the coil directly onto the

tooth (Fig. 6).

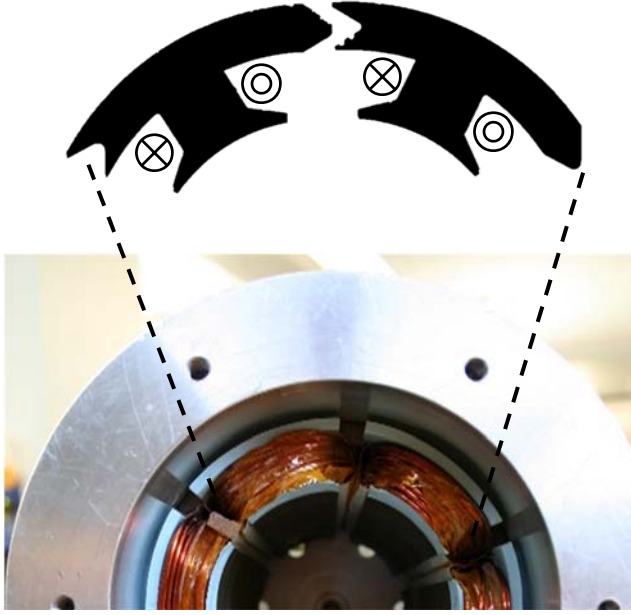


Fig. 6. Previously presented segmental stator (two sections), slot fill factor approximately 60% with very short end turns on the coils.

Figure 7 shows the presented novel stator segment structure of the tSynRM, where the coils are wound on a central tooth (for a single layer winding) and unwound teeth lock the coils into the slot.

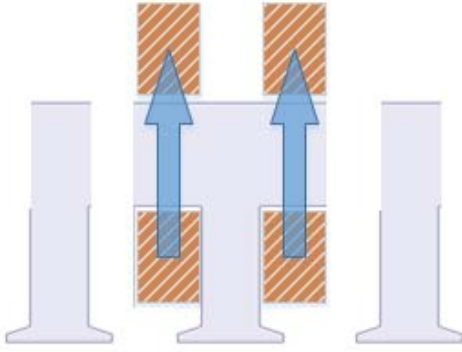


Fig. 7. Toroidal coil winding on segmental stator.

Using this method, high fill factors can be achieved, where it has been shown that upto 85% can be achieved if pre-compressed windings are used [17] in similar arrangements. In [13] a folded-strip arrangement (Fig. 8) was used for toroidal windings in an induction machine, where the tooth tips only exist over half the tooth for ease of winding and forming (bent into a circle) into the completed stator.

In mass production and manufacture, the folded-strip method may not be practical and the achieved fill factor may be lower than if segmentation was used. As a high tooth number would generally be used (>24) from small to large industrial motors, segmentation is particularly advantageous as

the stamped lamination would better utilize the raw material. The slot fill factor of an industrial motor with distributed windings is typically 30-35%, therefore by increasing the slot fill factor to 60%, the loss can be expected to half, in conjunction with the reduction in end winding length. The interlocking segments can be wound easily by hand but do lend themselves to automatic winding, which would improve the coil quality and reduce failure rate. Once automatically wound the stator can then be simply assembled and inserted into the case. The folded-strip-wound assembly would be rather long/bulky for larger diameter machines, the segmented stator concept is similar to another method presented in [12] but without the overlapped laminations. The segmental concept proposed here would rely upon shrink fit into the outer case to ensure air-gaps between segments are closed up and are as small as possible.



Fig. 8. Folded strip arrangement similar to that presented in [13].

A special outer case (toothed) would be required in order to clamp down onto the stator segments (Fig. 9) but allow space for the coils. Good ground wall insulation is required to minimize the possibility of coil shorts to the case, as this will usually be made from high conductivity aluminum, providing a good short circuit conduction path.

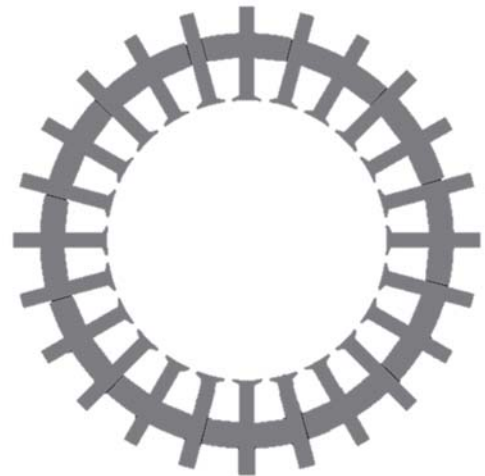


Fig. 9. Segmented stator with wound and unwound teeth and a castellated coreback.

## V. APPLICABILITY

In order for the windings to provide a positive benefit, the

total stator winding length per phase must be shorter than in a conventional machine. This leads to lower copper losses and increased machine efficiency. However, a machine aspect ratio change may be required (maintaining the same rotor electromagnetic volume) in order to achieve this. A larger outer diameter with a shorter stack length makes the end winding proportion increase in proportion to the axial conductor length, this in turn allows the condition for a shorter phase winding to be achieved, though it is beyond the scope of this present paper to detail the design of such a machine, but is intended rather to introduce the concept in relation to the fractional slot concentrated winding machine.

## VI. MACHINE PERFORMANCE

Electromagnetically, the performance can be expected to match that of a conventionally wound machine but with lower copper loss. The rotor design will change and the shaping of the flux barriers can utilize the extra space with increased diameter in order to optimize the design. Mechanical design of the rotor must be carefully considered at high aspect ratios, due to centripetal loading. Careful consideration of the radial and tangential rib thicknesses and placements must be a priority. With shorter stack lengths, the 3D effects will be more pronounced so 3D finite element analysis will be required in order to validate a design before prototyping.

## VII. CONCLUSION

The toroidal winding synchronous reluctance machine (tSynRM) has been presented for the first time. Previous topology changes introduced by the authors, such as the application of fractional slot concentrated windings (cSynRM) have significant advantages due to their short end windings, ease of manufacture and robust construction. However, parasitic effects caused by lack of slot pole combinations and even space harmonics limit their use. The proposed tSynRM allows the merits of the cSynRM to be essentially maintained whilst eliminating the even space harmonics and providing a wide range of acceptable slot pole combinations with good fundamental winding factors. There are a number of construction methods available, however the concept of segmentation as previously used on the cSynRM appears the most promising. Aspect ratio changes are required for the topology to be of benefit and special considerations in design are required, such as mechanical design of the rotor and taking into account the increased prominence of 3D effects. It is suggested that the machine electromagnetic performance (for identical rotor volume) will be maintained but with lower copper loss and higher efficiency possible. Detailed analysis of machine design and 3D effects is the subject of further research and publications.

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